Instanton Phenomenology at HERA

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in collaboration with

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and

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Copy available via WWW:

http://www.desy.de/~ringwald/dis97/talk.ps.gz

1. Introduction

- Hard scattering processes in strong interactions are successfully described in terms of the usual Feynman diagrams of perturbative QCD.
- Procedure behind Feynman diagrammatics:
  - Expansion of the Euclidean path integral expression for the corresponding Euclidean Green's functions

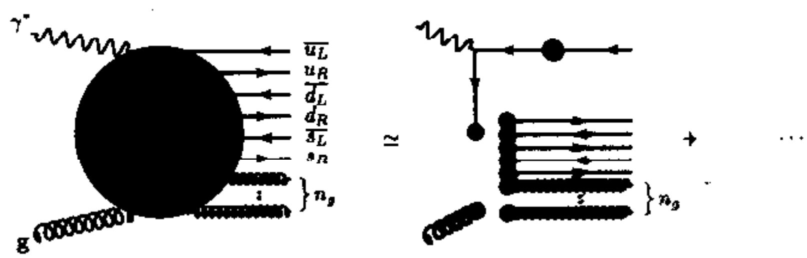
$$\frac{\int [dA][d\psi][d\bar{\psi}] A_\mu(x_1)\ldots\psi(x_i)\ldots\bar{\psi}(x_n)\exp\{-S[A,\psi,\bar{\psi}]\}}{\int [dA][d\psi][d\bar{\psi}]\exp\{-S[A,\psi,\bar{\psi}]\}}$$

    about the perturbative vacuum configuration, $A_\mu^{(0)} = 0$, with minimum Euclidean action $S^{(0)} = 0$.
  - Amplitudes: power-series in terms of α_s.
- The instanton $A_\mu^{(I)}(x)$ is a non-trivial solution of the Euclidean YM equations and thus a non-trivial local minimum of the Euclidean action with $S^{(I)} = 2\pi/\alpha_s$.
  - Expansion of the Euclidean path integral about the instanton can be summarized by modified Feynman rules.
  - Amplitudes: $\propto \exp\{-2\pi/\alpha_s\}$.
- In QCD with massless quarks usual perturbation theory and instanton perturbation theory describe two distinct classes of processes:
  - In usual perturbation theory, Green's functions corresponding to chirality (Q_5) violating processes vanish to all orders.
  - In instanton perturbation theory, only Green's functions corresponding to $\triangle Q_5 = 2n_f$ processes receive non-vanishing contributions.

- Example in DIS:
  Amplitudes for generic $\triangle Q_5 = 2\, n_f$ process,

$$\gamma^* + \mathrm{g} \Rightarrow \sum_{\text{flavours}}^{n_f} [\overline{\mathrm{q}_L} + \mathrm{q}_R] + n_\mathrm{g}\, \mathrm{g}\, .$$

  - Vanish to all orders in conventional perturbation theory.
  - Receive non-vanishing contribution from expansion about instanton:



  - Feynman rules and results: c.f. F. Schrempp's talk in WG V

- Close analogy to $B + L$ violation in electro-weak processes in the multi-TeV region. QCD-instantons however less suppressed than electro-weak instantons ($\alpha_s \gg \alpha_W$).

♣ An experimental discovery of such a novel, non-perturbative manifestation of non-abelian gauge theories would clearly be of basic significance.

- DIS at HERA offers a unique window to detect QCD-instanton induced processes through their characteristic multi-particle final-state signature.

2. Monte Carlo Generator QCDINS

[Gibbs, A.R., F. Schrempp '95 & in preparation; Carli, A. R., F. Schrempp, in prep.]

- "QCDINS 1.4.1": a Monte Carlo Generator for instanton induced processes in DIS, interfaced to HERWIG 5.8 (hadronization)
- Describe basic physics input and compare with results
  - Cross-Sections
  - Final-State Characteristics
  - Search Strategies for Instantons
  - Model-Dependent Extrapolation to Small x'

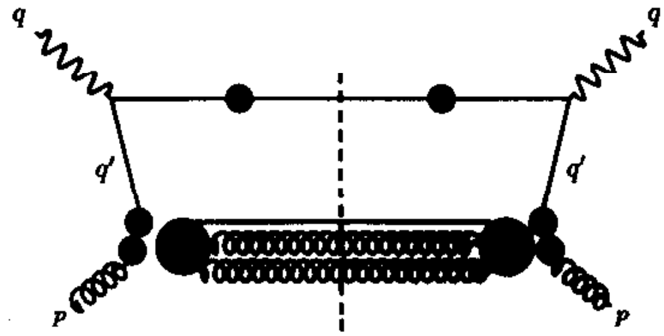
[redacted]

- I-induced contribution to nucleon-structure function in terms of parton-structure functions $\mathcal{F}_{i\,g}, \ldots, i = 2, L$, and densities $f_g, \ldots$:

$$F_2^{(I)}(x_{\rm Bj}, Q^2) = \sum_k \int_{x_{\rm Bj}}^1 \frac{dx}{x}\, f_k\left(\frac{x_{\rm Bj}}{x}\right) \frac{x_{\rm Bj}}{x}\, \mathcal{F}_{2\,k}^{(I)}(x, Q^2)$$

where $x_{\rm Bj} = Q^2/(2P_{\rm nucl} \cdot q)$.

- I-contribution to the (dominating) gluon structure function has the structure of a "handbag" diagram [Balitsky, Braun '93, A. R., F. Schrempp '96; Moch, A. R., F. Schrempp in prep.]:



- Yields nice momentum-space picture
  [A. R., F. Schrempp '96; Moch, A. R., F. Schrempp in prep.]:

$$\mathcal{F}_{2\,g}^{(I)}(x,Q^2) \simeq$$

$$x\sum_q e_q^2 \int_x^1 \frac{dx'}{x'} \int^{Q^2\frac{x'}{x}} dQ'^2\, P_{q^*/\gamma}^{(I)}(x,x',\frac{Q'}{Q})\, \sigma_{q^*g}^{(I)}(x',Q'^2)\,,$$

with $Q'^2 = -q'^2$, $x' = Q'^2/(2p\cdot q')$,

– "Splitting function", associated with the upper part of the "handbag diagram",

$$P_{q^*/\gamma}^{(I)}\left(x,x',\frac{Q'}{Q}\right) \simeq \frac{3}{16\,\pi^3}\,\frac{x}{x'}\left(1+\frac{1}{x}-\frac{1}{x'}-\frac{Q'^2}{Q^2}\right)\,,$$

– I-subprocess "total cross-section", containing essential instanton dynamics,

$$\sigma_{q^*g}^{(I)}(x',Q'^2) = \sum_{n_g} \sigma_{q^*g;\,n_g}^{(I)}(x',Q'^2) \simeq$$

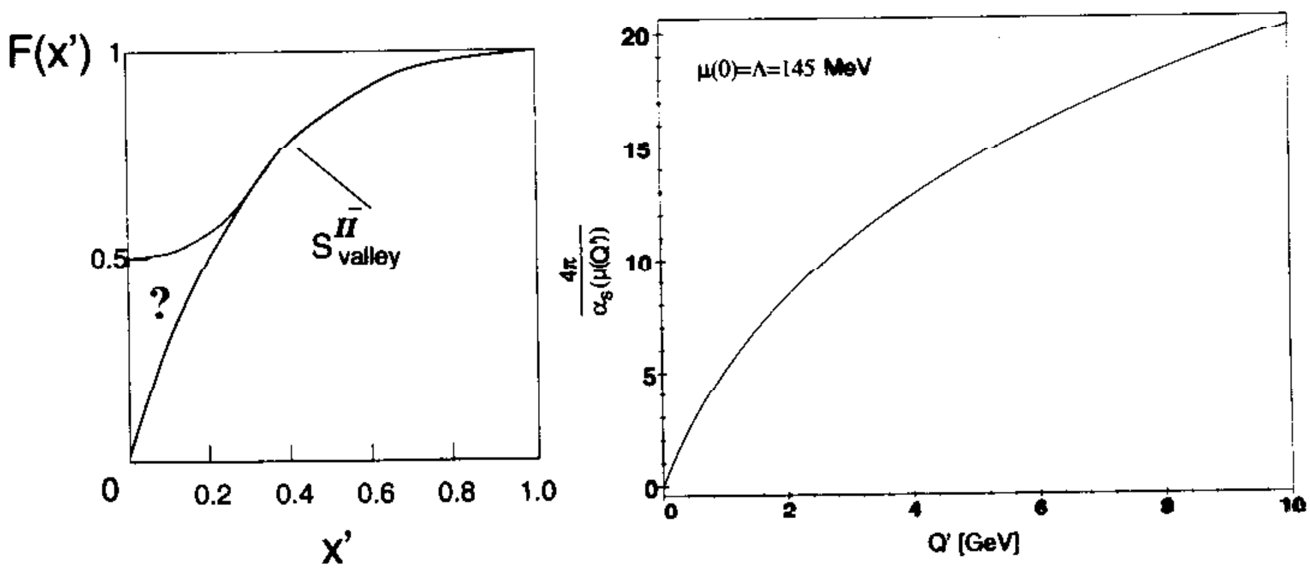
$$\frac{\Sigma(x')}{Q'^2}\left(\frac{4\pi}{\alpha_s(\mu(Q'))}\right)^{21/2} \exp\left[-\frac{4\pi}{\alpha_s(\mu(Q'))}\,F(x')\right]\,.$$

- Instanton-induced processes dominated by multi-gluon **production**:

$$\sigma^{(I)}_{q^*g;\,n_g} \propto \frac{1}{n_g!}\left(\frac{1}{\alpha_s}\right)^{n_g} \exp\{-4\pi/\alpha_s\}$$

  Exponentiates **in total cross-section: Exponential suppression factor modified by "Holy-Grail" function** $F(x')$. **In intermediate range** $0.2..0.3 \lesssim x' \leq 1$, **total cross-section** exponentially growing with decreasing x'.
  Due to inherent ambiguities can take result literally only for

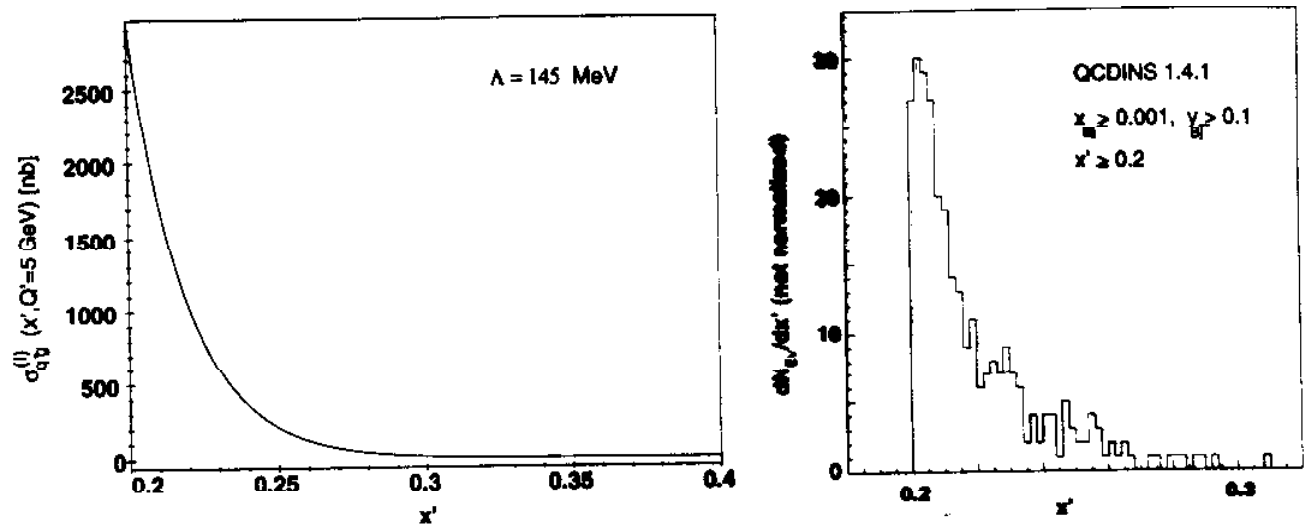
$$x' \geq x'_{\min} \simeq 0.2 - 0.3\,.$$



- **Effective** renormalization scale $\mu(Q')$, $\mu(Q') = Q'\alpha_s(\mu(Q'))/(4\pi)$, **should be large enough in order to have sufficiently small coupling** $\Rightarrow$

$$Q' \gtrsim 5\ \mathrm{GeV}\,.$$

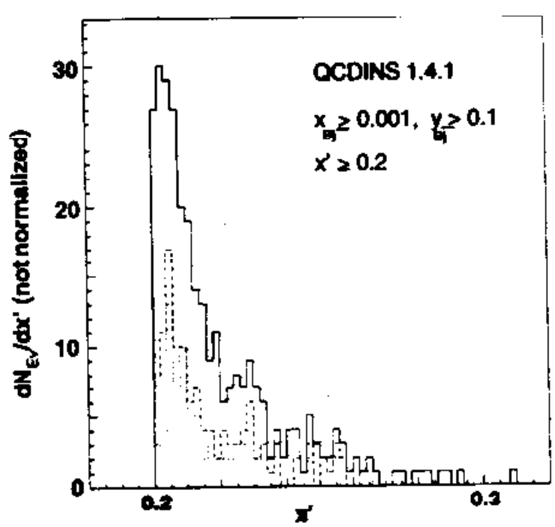
- Resulting x' dependence:



- Lower x' cut absolutely necessary.
- x' cut can be enforced, for example, by cutting

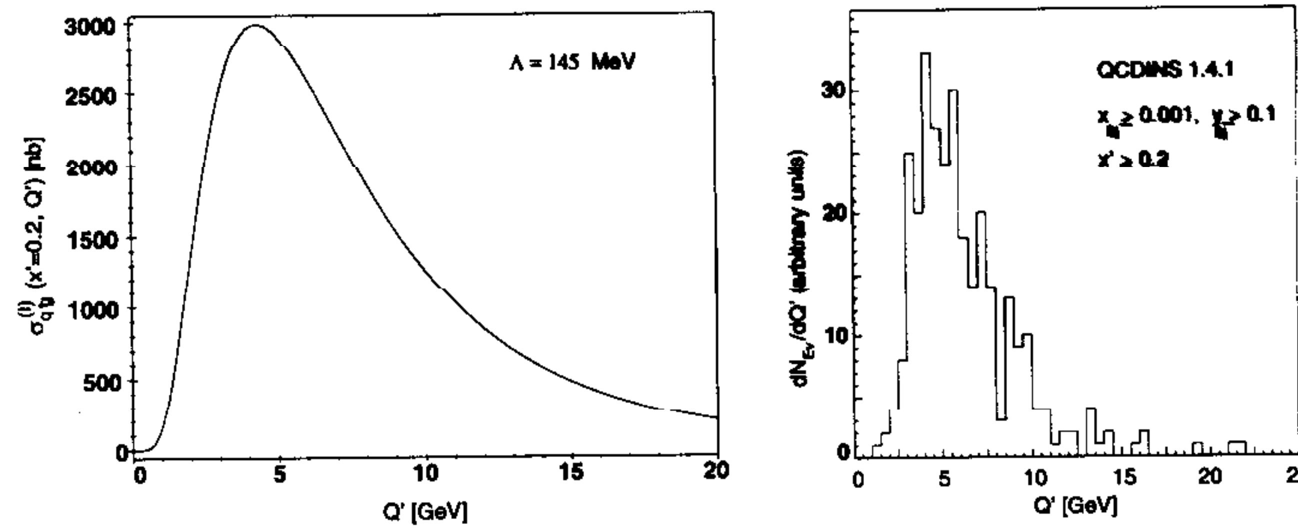
$$x \equiv x_{\mathrm{Bj}}/z \equiv Q^2/(Q^2+s),$$

from below, where z is the momentum fraction of the proton carried by the gluon and s is the $\gamma^* g$ c.m. energy.



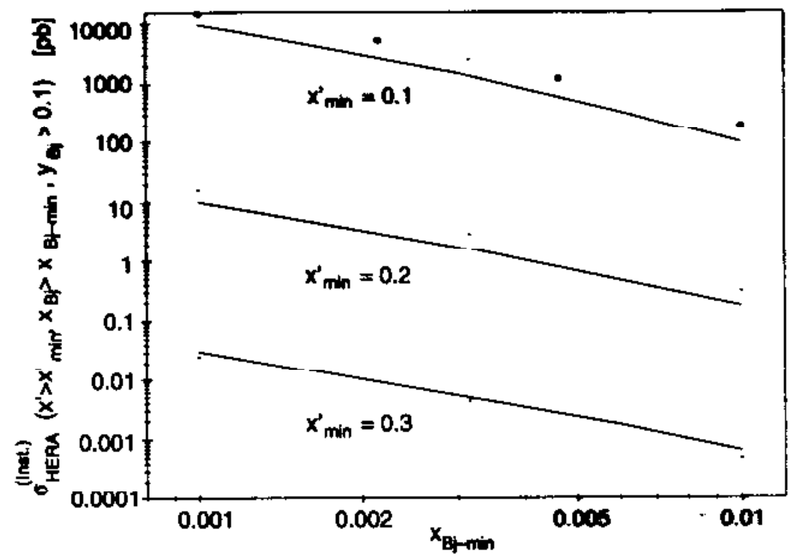
(dashed: $x \geq 0.1$; points: $x \geq 0.12$)

- Resulting Q' dependence:



- Lower Q' cut not mandatory (thanks to the chosen renormalization scale).
  - $\mathcal{F}^{(I)}_{2\,g}$ infrared insensitive.
    - Do not have to factor out collinear divergence into parton distributions.
  - $\mathcal{F}^{(I)}_{2\,g}(x, Q^2)$ independent of Q^2 for $Q^2 \to \infty$, i.e. scaling.
- Check of the Monte Carlo calculation of the instanton-induced contribution to the eP cross-section at HERA:
  - "Theory":
    - Take gluon distribution at a fixed reference scale.
    - Use the asymptotic scaling result for $\mathcal{F}^{(I)}_{2\,g}(x, Q^2)$.
    - Perform all the necessary integrations analytically.
  - Monte Carlo:
    - Use same gluon distribution.
    - In order to simulate the scaling limit ($Q^2 \to \infty$), use in the Monte Carlo very small $\Lambda = 0.2 \cdot 145$ MeV.
    - Take the cross-section from the Monte Carlo output.

Result:

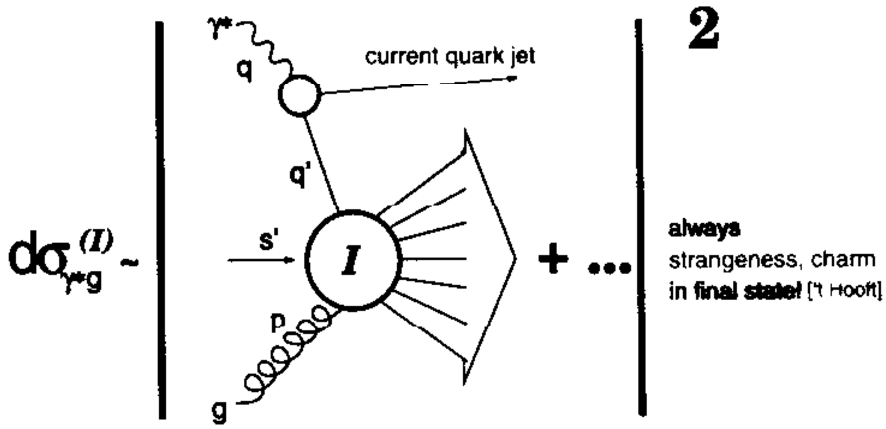


Nice agreement between "theory" (lines) and QCDINS 1.4.1 (points).

- Very strong dependence on x'_{min}.
- Thorough investigation of inherent renormalization- and factorization-scale dependencies is presently under way.

[redacted]

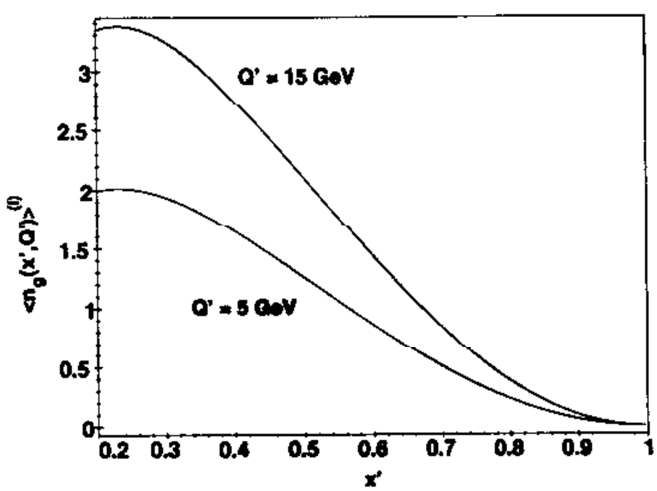
[A. R., F. Schrempp '94 & in prog.; Balitsky, Braun '93; V.V. Khoze, A. R. '91; 't Hooft '76]

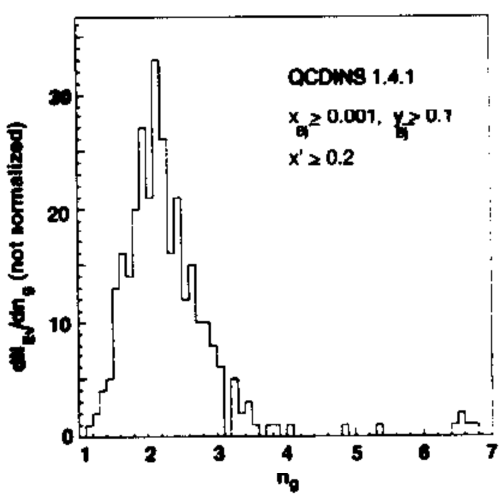


- Isotropic **emission of** many **semi-hard partons in $\boldsymbol{I}$-rest system**: "decaying fireball"
  - High multiplicity: **At least $2\,n_f = 6 - 8$ quarks plus a few gluons,**

$$\langle n_g(x', Q')\rangle^{(I)} \simeq \frac{2\pi}{\alpha_s(\mu(Q'))}\, x'(1 - x')\frac{dF(x')}{dx'}.$$

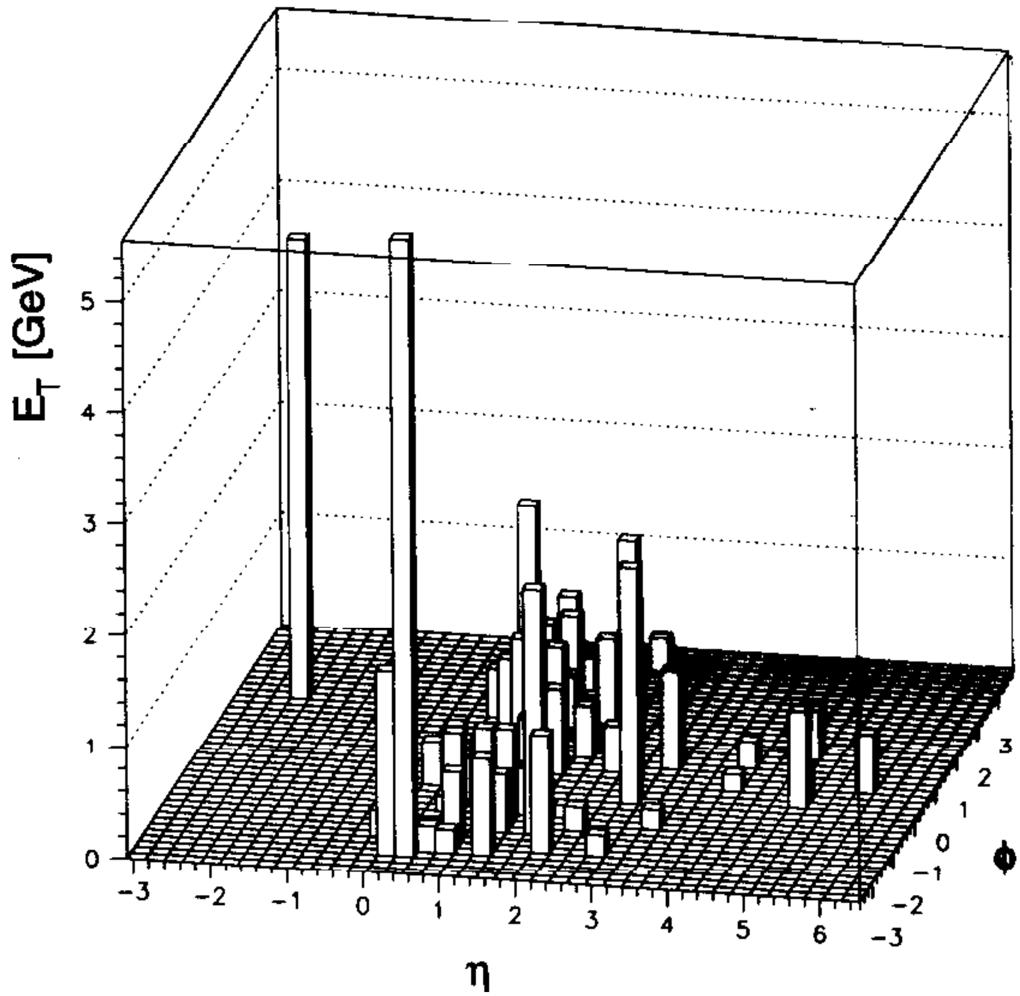
  - Multiplicity distribution: $\mathbf{lim}_{\mathbf{Bj}}\, \sigma_{n_g}{}^{(I)\,\mathbf{excl.}} =$ Poisson





  - **Characteristic flavor flow** (strangeness, charm)

- [redacted]

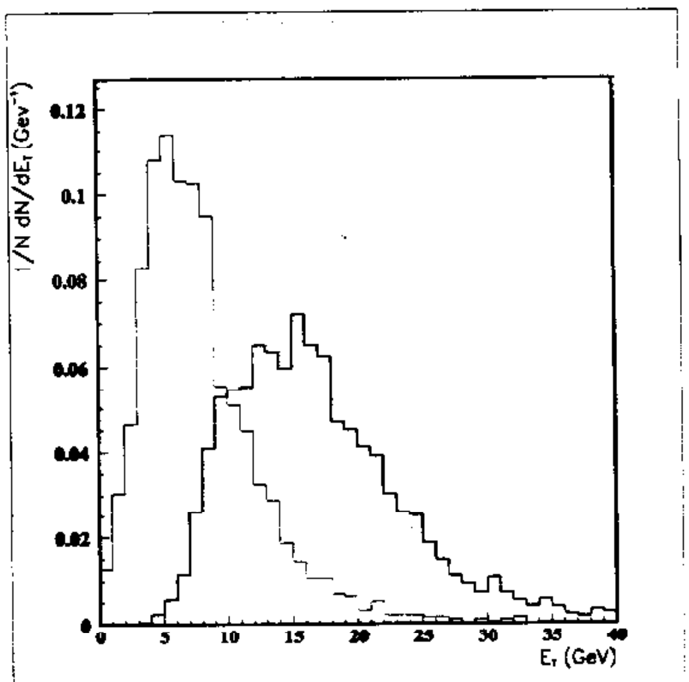


- Current jet
- Hadronic "band": ⇔ **isotropy in I-rest system**
  - ∗ Large total $E_T = \mathcal{O}(20)$ GeV
  - ∗ **Large multiplicity** $N_{\text{band}} = \mathcal{O}(25)$
  - ∗ No jets in "band" !
  - ∗ Characteristic flavor flow:

    ⋆ **Strangeness** ⇒ K_S^0's ⋆ **Charm** ⇒ μ's

- Limits from existing HERA data: c.f. T. Carli's talk later.
  - Searching for excess in multiplicities (all particles; Kaons), total transverse energy . . .
- Possible Search Strategies:

  [Gibbs, Greenshaw, Milstead, A.R., F. Schrempp, Proc. "Future Physics at HERA", 1996]
  - Combine event shape information with multiplicity cuts, transverse energy cuts and searches for K^0's and μ's.
  - Analysis in $\gamma - P$ rest-system:
    * In this system, (1+1) and (2+1) jet perturbative QCD processes deposit their energy predominantly in a plane passing through the $\gamma - P$ direction.
    * Energies from I-induced events are always distributed much more spherically (ISOTROPY!).
    * I-induced events have large $\langle E_T \rangle$! (Fig.)

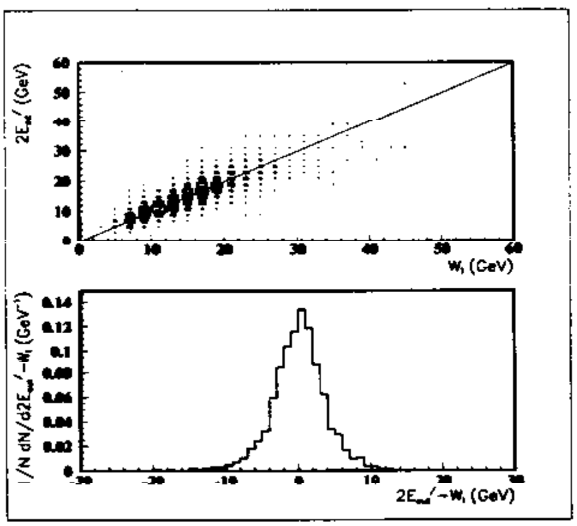


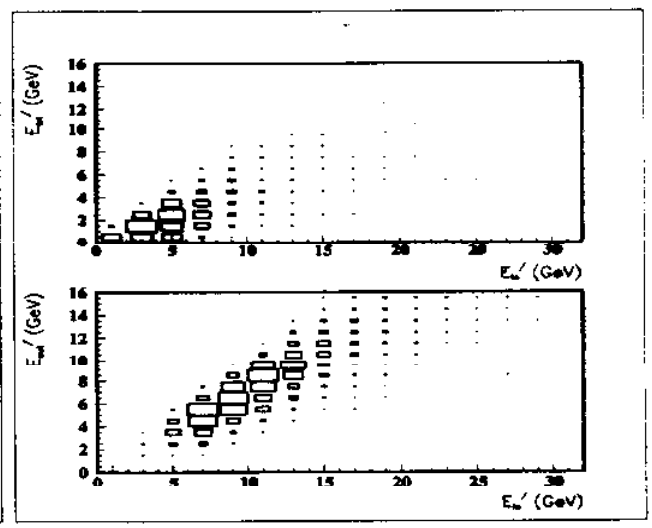
– Reduce normal "DIS" background by minimizing, on an "event-by-event"-basis,

$$E_{\rm out} = \min_{\hat{i}} \sum_{k}^{n} \mid \vec{p}_k \cdot \hat{i} \mid ,$$

by choice of $\hat{i}$ normal to the $\gamma - P$ direction.

– Standard (2+1) jet events (boson gluon fusion) have small $E_{\rm out} = \mathcal{O}(\text{jet width})$, while for I-induced events $2E_{\rm out} \approx \sqrt{s'} \equiv W_I$ large! (left Fig.)





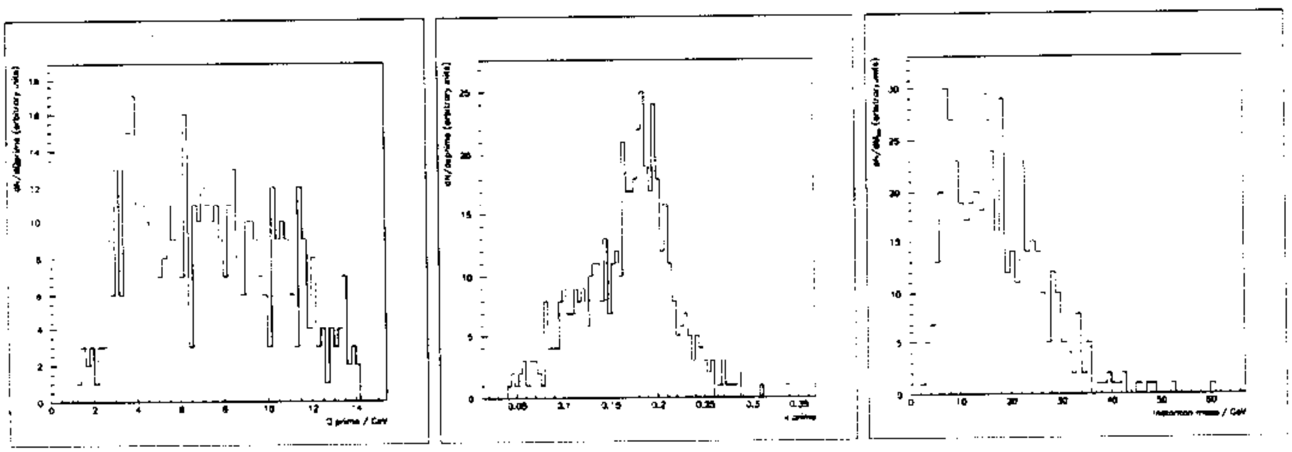
– $E_{\rm out}$ vs. $E_{\rm in}$ distributions in $\gamma - P$ c.m. system for $0.001 < x < 0.01$, $0.1 < y < 0.6$ and $20 < Q^2 < 70$ GeV^2. Normal "DIS" events (upper right Fig.), I-induced events (lower right Fig.).

[redacted]

- So far, we imposed always strict x' cut, $x' \geq x'_{\rm min} \simeq 0.2 - 0.3$, in order to be in the fiducial region of instanton calculations.
- Explore influence of region of smaller x' with a simple model,

$$\sigma^{(I)}_{q^*g}(x', Q'^2) = \sigma^{(I)}_{q^*g}(x'_{\rm min}, Q'^2) \text{ for } x' < x'_{\rm min}.$$

- Resulting distributions of I-subprocess variables:
(QCDINS 1.1; $x_{\rm Bj} \geq 10^{-2}, y_{\rm Bj} \geq 0.1, x'_{\rm min} = 0.2$)



  - Q'-distribution: same as before.
  - x'-distribution: peaks at $x'_{\rm min}$; suppression below $x'_{\rm min}$ is due to gluon density
  - M_I-distribution: peaks at $\mathcal{O}(15)$ GeV; note that

$$M_I \equiv \sqrt{s'} = Q'\sqrt{\frac{1-x'}{x'}}$$

  - Model shows essentially same features as model-independent analysis with strict x' cut, since most of the events come from the region in x' where the exponential growth of the cross-section stops.

3. Conclusions

- Discovery of QCD-instanton induced events of basic importance:
  - Novel, non-perturbative manifestation of QCD
  - Analogy to anomalous B+L violation in electro-weak processes in multi-TeV region
- [redacted]
- Monte Carlo event generator QCDINS approaching reliable and stable version.
- Decisive search for instanton-induced events at HERA seems feasable.